A METHOD OF DETERMINING THE RADIANT LUMINOUS EFFICIENCY OF A LIGHT SOURCE BY MEANS OF A CELL WHOSE TRANSMISSION CURVE IS IDENTICAL WITH THE LUMINOSITY CURVE OF THE AVERAGE EYE

DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES
OF THE JOHNS HOPKINS UNIVERSITY
IN CONFORMITY WITH THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

BY

ENOCH KARRER

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A METHOD OF DETERMINING THE RADIANT LUMINOUS EFFICIENCY OF A LIGHT SOURCE BY MEANS OF A CELL WHOSE TRANSMISSION CURVE IS IDENTICAL WITH THE LUMINOSITY CURVE OF THE AVERAGE EYE.[1]

BY ENOCH KARRER.

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CONSIDERABLE work has been done upon the subject included in the above title, under the names of "luminous efficiency" and "radiant efficiency." Very little of it, however, can have any bearing upon or connection with other photometric quantities, because in most instances no account was taken of the fact that all radiation in the visible spectrum is not equally powerful in producing light.

By the radiant luminous efficiency of any source is meant the ratio of the energy of the radiation emitted *weighted in accordance with its effectiveness* in producing the sensation of light, to the energy of the total radiation emitted.[2] This may be indicated thus:

$$\text{Radiant Luminous Efficiency} = \mu_R = \int_0^\infty \frac{E_\lambda (V_\lambda) d\lambda}{E_\lambda d\lambda},$$

[1] Abstract of this paper was read before the New York meeting of Physical Society October 31, 1914.

[2] For the definition of this quantity in relation to other suggested definitions of photometric quantities see H. E. Ives, Lighting Journal, Oct., 1913.

where V_λ is the visibility of wave-length λ obtained from the equal energy luminosity curve[1] of the normal eye; and $E_\lambda d\lambda$ is the energy at wave-length λ.

To see clearly what is meant by the luminosity mentioned above we may proceed as follows: Suppose we have a spectrum of a carbon filament lamp. If now we take from the region of wave-length .55 μ a certain amount of energy measured with a thermo-couple, say, and compare its brightness with the light of a candle, we will find a certain number representing its intensity, say one. Now, if energy is taken from some other region, say near wave-length .61 μ, we will find that for the same amount of energy we get approximately one half the candle power, or the number 0.5 representing its intensity. Thus we might go through the spectrum and determine the "light-value" of a definite and constant amount of energy at the various wave-lengths.

The equal energy luminosity of the observer's eye, then, is obtained by plotting the values determined above against the corresponding wave-lengths. This has been done by Ives[1] for many eyes; and a curve for the "average eye" has been obtained. This has a very important bearing upon many determinations and problems in photometry; and it is readily seen that the determination of luminous efficiencies made by merely selecting a certain region in the spectrum, from .4 μ to .72 μ as has been commonly done, without regard to the manner in which this radiation affects the eye, can have no accurate meaning in practice.

The object of the present research was to develop a method of measuring radiant luminous efficiencies according to the above considerations.

There are several possible modes of obtaining the quantity defined as the radiant luminous efficiency.

First. An energy curve of the source in question may be plotted. The ordinates of this curve represent the energy of the radiation at various wave-lengths (abscissæ). Now, if these ordinates be multiplied by the ordinates of the luminosity curve, representing the weight to be given each wave-length in producing light, we obtain numbers which will represent the light produced by each wave-length. A curve then may be drawn with these numbers as ordinates and wave-lengths as abscissæ. The area of this latter curve is proportional to the energy of the radiation properly rated as to its "light-value." The area included by the original energy curve measures the total energy of the radiation. The ratio of the former area to the latter gives μ.

Langley[2] and others have employed graphical methods for obtaining ratios of radiation weighted in different ways.

[1] Ives, Phil. Mag., Dec., 1912.

[2] Sci., June 1, 1883; Phil. Mag., May 30, 260, 1890.

Second. A screen with an aperture of suitable form may be used. This will be made clear by the following considerations:

Suppose we had a spectrum which had equal quantities of energy in the regions of every wave-length, and consider the radiation that passes through an aperture of the shape of the luminosity curve. The energy at each wave-length will be proportional to its light-giving power.

If, now, the spectrum of any source in question is formed with the same dispersing apparatus and allowed to pass through a screen with this aperture, the radiation from the source will be properly rated. We measure the energy in the spectrum after passing through the screen, and also the total energy without the screen. The ratio of the former to the latter is the radiant luminous efficiency sought. In unpublished work this method was suggested by Dr. Pfund in 1906; and also by Strache[1] in 1911.

Third. An absorbing solution may be made whose transmission curve is identical with the luminosity curve. Houstoun[2] has suggested the method. This is the method fully developed and described in this paper.[3]

Fourth.[4] Ives[5] has suggested the possibility of finding a photoelectric cell properly screened whose sensibility for various wave-lengths is of appropriate relative magnitude. Coblentz[3] suggests the possibility of finding a photoelectric radiometer with a sensibility curve that of the eye.

Fifth. A calorimetric method. This is described by Nichols[4] and it is not essential to describe it here. The purpose of the present investigation was to construct a cell with suitable absorbing solutions to be used in the direct determination of luminous efficiency. The transmission of such a cell must be such as to allow quantities of the radiation of any wave-length to pass through proportional to the luminosity of that wave-length; that is, the transmission curve must be identical with the luminosity curve of the average eye as given by Ives. The thermocouple screened with this cell in series with the galvanometer will respond to the radiation proportional to the true light value, that is, as the eye responds to that radiation giving the sensation of light.

The investigation is divided into two parts:

Part 1. An investigation of the transmission solutions contained in a quartz cell. The general method is obviously to measure the incident

[1] Proc. Amer. Gas Inst., 2, 401, 1911.

[2] Proc. Roy. Soc., 85 (A), 275, 1911.

[3] Phil. Mag., p. 853, Dec., 1912.

[5] Nichols, Lab. Manual, Vol. II., p. 325.

[3] A photographic method might be suggested here, with proper plates or plate in conjunction with suitable screen.

[4] Bul. B. of S., Vol. 9, page 46, 1913.

and transmitted radiation; and for this purpose a thermocouple was used. The scheme of apparatus used in this part is shown in Fig. 1.

The current through the Nernst glower was maintained at 0.8 ampere by potential from a storage battery. The carbon arc was tried as a source for radiation in the violet, but was found entirely unsatisfactory due to unsteadiness. The Nernst glower was used throughout the investigation of the transmission of solutions. The glower was protected from air currents by a small wooden box lined with heavy asbestos, which was just sufficiently large to receive the metal casing in which the filament

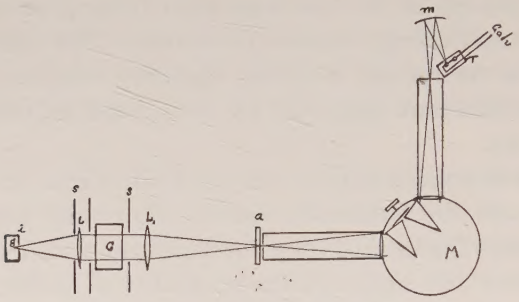

Fig. 1.

g = Nernst glower in inclosure i.
l, l_1, lenses.
s, s_1, screens.
c, cell containing solutions to be investigated.
a, auxiliary cell.
M, monochromatic illuminator.
m, silver concave mirror.
T, thermo-element.

was mounted. The box has a brass door with an aperture to allow full illumination of the first lens surface.

The lenses l, l_1 had a focal length of 14.5 cm. and diameter of 4 cm. Screen s was of heavy cardboard with a circular aperture of diameter somewhat less than 4 cm. so that the side walls of the cell (c) were not illuminated.

The cell (a) contained clear distilled water or a concentrated solution of copper chloride; the former when the longer wave-lengths were used, the latter when short wave-lengths were used. This auxiliary screen was placed as near as possible to the receiving slit of the illumination. It was designed to avoid the vitiating effects of scattered radiation.

The monochromatic illuminator was calibrated by means of the following lines: potassium 7,682, lithium 6,708, sodium 5,893, mercury (arc) 5,780, 5,461, 4,916, 4,358, 4,078. This calibration was checked several times during the work to detect any instrumental shifts. The light from

the transmitting slit was focused upon the thermocouple (T) by means of a short-focus concave silvered mirror (m). This was kept well polished always.

The thermocouple used in this part of the work was one constructed by Dr. Pfund[1] and used by him in measuring stellar radiation.[2] The thermo-element was enclosed in a sealed tube with a fluorite window. Evacuation was accomplished by means of Pfund's charcoal evacuator.[3] The degree of exhaustion was tested several times during the progress of the work and no diminution was noted even after months of service. For a detailed description the reader is referred to the original papers.[3]

The thermo-element was fastened securely in a box. Short leads connected its terminals with two large copper plates, also securely fastened in the box. Two additional wires led from the copper plates backwards. The box was then entirely filled with fine sand, to protect the thermo-element from convection currents. The copper plates were designed to act as heat reservoirs, so that conduction of heat energy to the thermal-element through the external leads would have little effect upon the galvanometer system. Over this box—with a suitable aperture to receive the light—was placed another box lined with heavy paper.

The galvanometer used in conjunction with the thermo-element was of a D'Arsonval type and was constructed by Dr. Pfund. It was designed to be quite stable and have sensibility sufficient for the present purpose. The suspension was of silver and about 10 cm. long. It was provided with a concave mirror approximately 2.5×3.5 mm. and of long focal length. Its period on open circuit was 15 sec. The galvanometer was enclosed in a box mounted upon an outside brick wall. The box was loosely packed with cotton. The mirror was seen through an aperture in the front of the box. This was covered with a thin strip of glass during the greater part of the work. The scale mounted upon ground-glass was four meters from the galvanometer and was supported upon a bracket securely fixed to a brick wall also. The image of a filament of an incandescent lamp was formed upon the ground-glass. The deflections were read with a hand glass magnifying about two and one half times. Later in the work advantage was taken of the diffraction images formed by the small mirror. With the reading lens the maxima and minima were very sharp and very easily seen.[4] The first dark space was about

[1] Phys. Zeit., 13, 870, 1912; PHYS. REV., XXXIV., 228, 1912.

[2] Pub. Allegheny Observatory, III., No. 6, p. 43.

[3] Phys. Zeit., 13, 870, 1912.

[4] Many maxima and minima could be seen sharply defined on either side of the central bright image.

the width of the lines on the scale. This first dark space was used instead of the bright central image. This proved to be a very convenient and accurate method of reading the deflections. The method was first suggested and tried by Dr. Pfund. A sliding holder for the lens was constructed so that the diffraction image could be followed more comfortably as the mirror deflected. A little scale rider graduated to tenths of millimeters was made. This could be pushed along with the lens to aid in estimating fractions of a millimeter. For the most part tenths of millimeters were estimated without the aid of the rider. The galvanometer system was remarkably free from accidental disturbances. There was very little drift of the zero point except owing to the extreme variations in the room temperature from morning to night. During the latter part of the work the space between the scale and the galvanometer was enclosed by means of tin pipe to avoid the scintillation of the image due to convection currents in the air. The galvanometer with the thermo-element in series with it was just critically damped. This condition was accurately brought about by adjusting an iron bar across the poles of the field magnet. The sensibility of the galvanometer and thermo-couple was such as to give 26 cm. deflection when a candle was placed at a distance of 1 meter in front of the thermo-element.

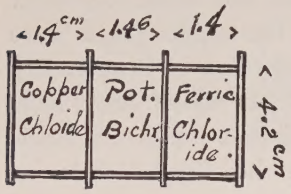

Fig. 2.

The deflections of the galvanometer were accurately proportional to the energy falling upon the thermocouple. This had been established by Dr. Pfund in a long series of tests made in the course of previous work.

The cell which contained the solutions investigated had three compartments as shown in Fig. 2. It was made from three rings cut from ink bottles. The rings were ground to have approximately parallel edges. They were cemented, by means of Canada balsam, end-on with quartz plates between and at both ends. The plates between the rings were 42 × 42 × 1 mm. while those at the ends were circular 42 mm. in diameter and 2 mm. thick. An opening was cut into each ring for purposes of filling. The quartz plates were purchased from The John A. Brashear Co. and the Bausch & Lomb Optical Co. They were only approximately plane parallel, but they were so placed on the rings that their individual defects were largely neutralized. The quartz plates were adjusted also so that the completed cell had quite perfectly parallel surfaces. This was tested by inserting the cell filled with water in front of a telescope focused on a distant church steeple. There was some

prismatic effect in the vertical plane; but this was not objectionable since it would cause a displacement of the image of the Nernst filament lengthwise along the slit of the monochromatic illuminator. When only one or two solutions were investigated the other compartment was filled with water. All the data given below were obtained with this cell. Other cells had been constructed and tried. They were made of plane parallel glass, but slight selective absorption of wave-lengths between .56 μ and .59 μ was noticed. On this account the cells were discarded. Quartz, on the other hand, offers a great advantage in that it can be readily duplicated.

The method of making determinations was as follows:

The solutions were put into the cell; the graduated head of the illuminator set to give the desired wave-length; the thermoelement was exposed to this wave-length first when the above cell was in the optical path and, second, when it was out; the ratio of the deflection in the first case to the deflection in the second case gives the percentage of transmission.

Determinations of this kind were made throughout the visible spectrum at intervals of .01 μ. These percentages of absorption were plotted against wave-lengths, that at .55 μ being taken as unity because this is the wave-length of maximum luminosity. This curve could then be compared with the luminosity curve[1] plotted to the same scale. To obtain a rough idea of the transmission curve of any set of solutions readings were made at .55 μ, .51 μ, .48 μ, .60 μ and .64 μ. This was sufficient to show what must be done to the solutions to approximate the luminosity curve, or whether they were suitable at all.

The slits used were as small as possible and still allow deflections accurately readable. In the extreme blue the widths were approximately 0.4 to 0.6 mm.; in the longer wave-lengths much less—in the red less than 0.1 mm.; at wave-length of maximum luminosity the slit width was approximately 0.2 mm. No corrections were applied for slit width.

There was always present a slight amount of stray light, through the monochromatic illuminator. In the final cell, however, with its high transmission, this was comparatively small. In the extreme blue, where large slits had to be used, another method was adopted as a check. A thin glass cell was made, filled with concentrated potassium bichromate solution. This was inserted immediately in front of the first slit of the illuminator. The opaque screen was raised; and, when the galvanometer became steady, the little cell was suddenly removed. The additional deflection was noted. This was entirely due to the blue at which the

[1] H. E. Ives, "Spectral Luminosity Curve of the Average Eye," Phil. Mag., Dec., 1912.

illuminator was set and which was out when the bichromate screen was in place. To avoid any displacement of the image of the Nernst filament and change in focus when the bichromate screen was taken out and replaced, the latter was immersed in a water cell which was always in front of the slit. The optical path was thus kept practically constant.

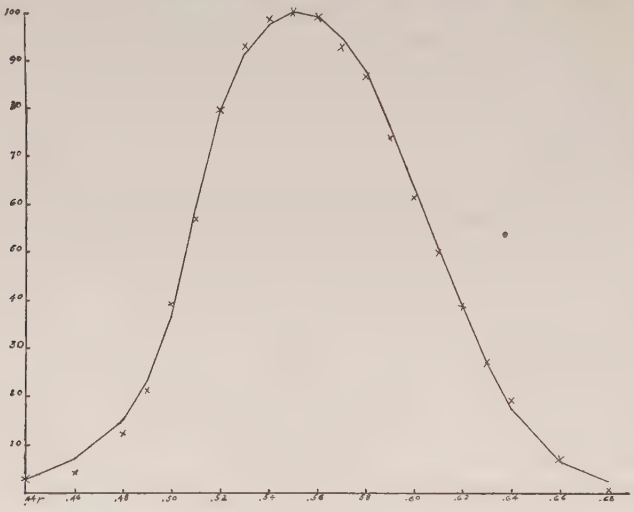

Fig. 3.

Transmission curve of cell in crosses Luminosity curve in full line.

It was found that the shifting of the zero noticed at the beginning of a series of observations could be eliminated quite completely by opening the slits and exposing the thermocouple for several minutes to the radiation from the Nernst glower. After this exposure the zero would remain constant.

Many inorganic salts were investigated; but only a few organic ones. Over two dozen dyes were examined in various combinations. The common difficulties with the dyes are that their absorption is high; they have sharp bands; and usually those having the adequate absorption near .60–.64 μ become again transparent in the infra-red. An additional objection is their instability and the uncertainty of exactly reproducing them.

The solutions that were found to answer requirements most satisfactorily with the cell above described were:

1. Cupric chloride ($CuCl_2 + 2H_2O$) purchased from Eimer & Amend. Analysis showing some trace of iron (0.0025 per cent.) and of sulphur (0.0016 per cent.) 41.085 grams of the salt were dissolved in one litre of distilled water. This solution was contained in the first compartment of cell 1.4 cm. in thickness.

2. Potassium bichromate ($K_2Cr_2O_7$, M. W. 294.5) purchased from J. T. Baker & Co., N. J. Analysis showing traces of calcium (0.001 per cent.) and of chloride (0.0001 per cent.) and sulphite (0.01 per cent.) 0.83462 gram per liter. This was contained in the middle compartment of the cell 1.46 cm. thick.

3. Ferric chloride ($Fe\ Cl_3$, $6H_2O$; M. W. 270.32) purchased from J. T. Baker & Co., N. J. Showing by analsyis P—trace, SO_3 0.002 per cent., HNO_3—trace, As—trace. 5.8712 grams per liter. Contained in the third compartment of the cell 1.4 cm. thick.

The concentrations of these solutions given above for thickness actually used become for a thickness of 1 cm. as follows:

Cupric chloride	57.5190 gm./l.
Potassium bichromate	1.2190 "
Ferric chloride	8.2200 "

The values for the transmission could be duplicated to within one per cent. on the red side of the maximum and to within four or five per cent. on the blue side. After four or five days the ferric chloride solution becomes opaque. Throughout the measurements made here this solution was prepared anew every other day. A certain percentage solution of iodine and potassium iodide can be substituted for the ferric chloride solution. This solution is .0515 gm. iodine with .4047 gm. potassium iodide to one liter of water. This iodine solution was used several days after preparation. It was contained however in a sealed jar. Whether there is any preponderating advantage to substitute it for the iron solution used cannot be stated at this time.

The values given in Table I. for the transmission are for the most part the means of four sets of data taken when the cell had been filled anew with new solutions. In each set three or four readings were taken at each wave-length. The measurements were taken at room temperature (about 19° C.). The temperature coefficient is too small to cause any noticeable change in absorption for a variation of a few degrees. The variations from the mean are less than 5 per cent. with the exception of three readings at 52, 54 and 55; considerably less in most cases, particularly on the red side of the maximum.

The deflections obtained without the cell were: At .50 μ 27.7 mm.; at .55 μ 39 mm.; at .60 μ 29 mm.; at .64 μ 45 mm.

Table I. shows the absolute transmission T in per cent. and the relative transmission T_r. Under V are given the corresponding values of the luminosity.[1] In column 1 are the wave-lengths; in column 2, the percentage transmission; in column 3, relative transmission, with that at .55 μ taken as 100; in column 4, the corresponding values for the

[1] Ives, Phil. Mag., Dec., 1912, p. 859.

TABLE I.

λ		T_r	V
.44μ		2.0	2.9
.46		4.0	7.3
.48	7.4	12.3	15.4
.49	12.8	21.3	23.5
.50	23.6	39.2	36.3
.51	34.2	57.0	59.6
.52	47.6	79.3	79.4
.53	55.9	93.0	91.2
.54	59.1	98.5	97.7
.55	60.0	100.0	100.0
.56	59.6	99.2	99.0
.57	55.4	92.5	94.8
.58	51.9	86.5	87.5
.59	44.4	73.8	76.3
.60	37.1	61.5	63.5
.61	30.0	50.0	50.9
.62	33.3	38.7	38.7
.63	16.3	27.1	27.2
.64	11.7	19.5	17.5
.65	4.3	7.1	6.8
.68	1.0	1.7	2.6

luminosity taken from Ives.[1] Below .48 μ and above .68 μ the curve is extended, for no readings here were taken. At .70 μ there was practically zero transmission; beyond .70 μ there was also zero transmission. The amount of energy given by the Nernst glower in wave-lengths below .48 μ is so small that a very large slit must be used and the measurements are very inaccurate. The transmission, however, extends down to .43 μ as is shown by the fact that the line of the mercury arc at .43 μ can be plainly see through the cell.

In Fig. 3 are given the transmission curve in crosses, and the luminosity curve of the average eye as found by Ives in full line. By means of a planimeter the areas of these curves were obtained. The area of the transmission curve is about 2.9 per cent. smaller than that of the luminosity one. It will be observed, however, that it is in the extreme blue where the maximum difference between the curves exists. In this region most light sources are deficient, so that the errors committed by using the cell is certainly much less than this.

The value of a knowledge of the radiant luminous efficiency of a light source may not be obvious to the reader who is not engaged in photometry, or who is not a worker in the profession of the lighting engineer. This quantity gives us a very interesting and valuable characteristic of

[1] Ives, Phil. Mag., Dec., 1912, p. 859.

the light source. It has close associations obviously with the total luminous efficiency, *i. e.*, the ratio of the radiations rated according to their luminosity to the total energy-input into the light source. For, knowing the losses (*e. g.*, in the case of the filament lamp, losses due to convection, conduction and resistance of the lead-in wires) the total luminous efficiency may be found from the radiant luminous efficiency.

Knowing the radiant luminous efficiency we would also know the total luminous efficiency from another consideration. For if we knew the watt equivalent of unit flux density of light of any wave-length we can also readily find the total luminous efficiency. The quantity to which reference has just been made has been termed the mechanical equivalent[1] of light. In our calculations we must take the "mechanical equivalent" of the radiation at wave-length of maximum luminosity (550 $\mu\mu$).

Calling the lumens per watt or radiation of wave-length 550 $\mu\mu$, K_{max}, we have

$$\frac{1}{K_{max}} = \text{watts per lumen}$$

or

$$\frac{4\pi}{K_{max}} = \text{watts per mean spherical candle.}$$

The radiant luminous efficiency (μ_R) tells us that only μ_R per cent. of the total radiation is light when the radiation is properly valued. Therefore,

$$\frac{4\pi}{K_{max}} \div \mu_R = \text{watts per mean spherical candle.}$$

Again, to fully and definitely describe a light source this quantity must be known. This will be seen by the following considerations. We may have two light sources which have the same value for the total luminous efficiency, *i. e.*, they may have the same energy-input and give the same amount of light radiation. Yet they may have quite different values of radiant luminous efficiency. The total luminous efficiency gives us the quantity which is most important from the economic standpoint; but is not by any means the only characteristic which we wish to know and must know for further development of our light sources.

In order that this quantity may mean what it should, however, all effects of radiation from mechanical parts connected with the source must be eliminated. The energy radiated only from the primary incandescent or luminous parts must be considered. This means that correc-

[1] Since the above work has been done Dr. Ives, Dr. Coblentz and Mr. Kingsbury have made an accurate determination of this quantity.

tion must be made for radiation from the chimney, from the bulb or other enclosure, and from the envelope of hot gases in case of certain sources. For this reason great accuracy for the values given below cannot be claimed. Correction was made only for one of the sources studied. The full significance of what errors due to this cause may be was fully realized in case of the mercury arc. Possibly to the illuminating engineer it is of greater usefulness to know the radiant luminous efficiency of the light source as it is used, that is without the corrections above applied.

It is obvious that the radiation measurements are not measurements involving in actual procedure the whole of the energy of radiation from the source; a particular direction and a particular solid angle are chosen. The direction is such as is usually of greatest interest for other measurements of the light sources studied.

Strictly in accordance with definition the whole energy of radiation in each case should be considered. The values obtained for the radiant luminous efficiency may be quite different in different directions. This must be so in case of the carbon arc and mercury arc and acetylene burner.[1] This has not been investigated and the author is not aware that any work or statement has been made upon this point. We might define other quantities such as the mean horizontal and the mean spherical value of the radiant luminous efficiency to be in correspondence with the measurements of candle power.

Part II. With this cell it was purposed to determine the radiant luminous efficiency of various light sources. This has only in part been

Fig. 4.

T, thermo-element with enclosure *b*.
s . . . *s*, screens.
g, galvanometer.
l, light source investigated.
C, cell.

accomplished; a few of the many sources have been studied, and all necessary corrections perhaps have not been applied.

The general arrangement of the apparatus for this portion of the work is shown in Fig. 4 above.

[1] Bul. Bur. Stand., Vol. 7, 1911.

This portion of the work was carried out, in most part, in the research laboratory of the United Gas Improvement Co. of Philadelphia, where access was had to various standard sources authoritatively rated. The new type of Leeds & Northrup galvanometer was used. The scale and telescope were at a distance of two meters from the galvanometer. This was made possible by placing immediately in front of the galvanometer a spherical concave spectacle lens (.25). Tenths of millimeters could easily be estimated for the image of the scale was almost natural size.

A Ruben's thermopile was used. This was employed instead of Pfund's thermocouple to avoid the uncertainty of absorption by the fluorite window for the various light sources.

About 22 cm. deflections were obtained with a candle at the distance of a meter. There was a very great lag, however, and a steady drift of the zero. Though the critical damping resistance of the galvanometer was 32 ohms this damping was not present when much greater resistance was inserted. To overcome this and the uncertainty as to what the effective distance was with a metallic cone before the junctions, the thermopile was dismantled of all its metal parts and mounted on a block of wood enclosed in a small pasteboard box with suitable aperture. Fine short leads connected it to two large pieces of brass cylinder; from which in turn two fine leads extended outwards. This box was loosely packed with cotton and enclosed in a second larger box mounted upon a long photometer bench constructed for the purpose. This last was also packed with cotton. There was now much less lagging and drift, though a considerable loss of sensibility was sacrificed. A series of screens was made of heavy cardboard mounted upon suitable blocks to fit the photometer bars. These screens had apertures of gradually decreasing size. They were stationed at intervals of from 10 to 20 cm. along the bar between the light source and the thermocouple.

The cell was mounted upon a small frame for which an appropriate sliding space with stops was arranged, so that the cell would be pushed aside and replaced in exactly the same position. The cell was placed as near as possible to the thermopile. Accurately round apertures in a thin board were painted black and placed immediately before and behind the cell. These apertures were a trifle smaller in diameter than the cell, to prevent any reflected light not going through the cell from reaching the thermopile.

The angle subtended by the thermopile at a distance of 63 cm. was one whose cross-section was 4 cm. horizontally by 22 cm. vertically. This angle was sufficiently large to include the whole surface of most of the illuminants investigated

The galvanometer deflections in the ranges occurring throughout the experiment were proportional to the energy falling upon the thermocouple. This was borne out for some very large deflections where the deviation was well under one per cent. The time required to reach a maximum deflection was approximately twenty-five seconds.

To take a set of measurements the light source was moved to a convenient distance; the thermoelement was exposed by raising a screen of heavy card suitably connected to a system of pulleys easily operated by the observer at the telescope; the maximum deflection was noted (the zero before and after being also noted); the cell was now pushed into position; the light source was moved sufficiently nearer, and a similar set of readings taken; the cell was then removed; the light source moved out to its first position and readings repeated. From ten to twenty readings were taken for each setting. For most of the sources recorded a similar series was taken on the two different days. There

TABLE II.

Welsbach Mantle Ceria 2 Per Cent. with Cell.

Zero.		D	r_v
Before.	After.		
2.30	2.10	3.70	1.50
2.10	2.10	3.65	1.55
2.10	2.10	3.80	1.70
2.10	2.13	3.75	1.64
2.13	2.25	3.86	1.67
2.25	2.35	3.97	1.67
2.35	2.50	4.11	1.69
2.65	2.80	4.45	1.73
2.80	2.90	4.60	1.75
2.90	3.05	4.55	1.58
2.42	2.60	4.16	1.65
2.60	2.62	4.25	1.64
2.62	2.70	4.32	1.66
2.70	2.78	4.15	1.41
2.78	2.90	4.55	1.71
2.90	3.00	4.56	1.61
3.00	3.05	4.70	1.68
3.05	3.20	4.75	1.63
			Mean 1.63

was always some drifting of the zero; and, though the galvanometer was mounted in the basement on the stone wall, accidental deflections due to mechanical disturbances from the mechanic's shop on the first floor were often considerable. The galvanometer suspension was very short,

which made such effects much more pronounced. The errors resulting from these sources were reduced by the large number of observations made.

Results.—A series of typical readings for the Welsbach mantle (2 per cent. ceria) with the cell is given in Table II.; for the same without the cell in Table III.; for the carbon point source ($4w/c$) readings with and

TABLE III.

Mantle 2 Per Cent. Ceria. Without Cell.

Zero.		D	r_t
Before.	After.		
2.15	2.10	24.46	22.34
2.10	2.32	24.82	22.61
2.32	2.40	24.95	22.59
2.40	2.25	24.96	22.62
2.25	2.08	24.90	22.74
2.08	1.85	24.75	22.79
1.85	1.82	24.60	22.77
1.82	1.70	24.49	22.73
1.70	1.58	24.47	22.83
1.58	1.40	24.30	22.81
1.40	1.38	24.20	22.81
1.10	0.93	23.70	22.69
0.93	0.80	23.75	22.92
0.80	0.43	23.55	22.91
2.35	1.95	25.50	23.35
1.80	1.55	24.47	22.80
1.55	1.30	24.40	22.98
1.20	0.95	24.12	23.05
0.95	1.10	23.98	22.96
1.10	0.95	24.05	23.03
0.67	1.10	24.45	23.57
1.00	1.00	24.25	23.25
0.85	0.70	24.15	23.43
0.40	0.20	23.80	23.50

without the cell are given in Table IV., and Table V. respectively; for the new tungsten-nitrogen filled lamp (.65 w/c) in Tables VI. and VII. respectively.

In columns one and two of each table are given the positions of the zero point before and after deflection; in column three, the observed maximum deflection; in column four, the true maximum deflections (r); (*i. e.*, column three corrected for position of "zero" as given by columns one and two).

In Table VIII. the means for all the sources studied are given, together with the corresponding distances and the ratio μ defined as the radiant

TABLE IV.

Carbon 99 v. (4 w/c). With Cell.

Zero.		D	r_v
Before.	After.		
2.47	2.50	4.75	2.27
2.50	2.48	4.78	2.29
2.48	2.48	4.70	2.22
2.48	2.57	4.80	2.28
2.57	2.55	4.81	2.25
2.55	2.58	4.82	2.26
2.58	2.64	4.90	2.29
2.64	2.70	4.99	2.32
2.70	2.72	5.00	2.29
2.72	2.80	5.01	2.25
2.80	2.87	5.17	2.34
2.87	3.00	5.24	2.31
3.00	3.05	5.37	2.35
3.00	3.08	5.33	2.29
3.08	3.13	5.40	2.30
3.13	3.15	5.43	2.29
3.15	3.20	5.48	2.31
3.20	3.30	5.58	2.33
3.30	3.40	5.63	2.28
3.40	3.40	5.70	2.30
			Mean 2.28

luminous efficiency. In column one are given the deflections (r_v) with the cell in place and with the source at a distance (d_v) as given in column three; corresponding quantities r_t and d_t without the cell are given in columns two and four. In column five is given the efficiency for each source.

The distances d_v are corrected for the change in optical distance due to the glass and water of the cell. This amounts to 0.7 mm. and was subtracted from the distances measured. All distances and deflections are given in centimeters.

μ has been defined above as

$$\frac{\text{Radiated energy} \times \text{luminosity}}{\text{total radiated energy}}.$$

With a cell whose transmission is identical with the luminosity curve this becomes

$$\frac{\text{Radiated energy} \times \text{transmission}}{\text{total radiated energy}}.$$

$$\mu = \frac{\int E_\lambda V_\lambda d\lambda}{\int E_\lambda d\lambda} = \frac{\int E_\lambda A_\lambda d\lambda}{\int E_\lambda d\lambda},$$

where A_λ is the absorption by the cell at wave-length λ.

TABLE V.

Carbon 4 w/c 99 v. Without Cell.

Zero.		D	r_t
Before.	After.		
0.00	−0.12	50.30	50.36
−0.12	−0.28	50.36	50.56
−0.28	−0.62	50.33	50.78
−0.62	−0.60	50.20	50.81
−0.60	−0.60	50.50	51.10
−0.60	−0.30	50.48	59.93
−0.30	−0.60	50.32	50.77
−0.60	−0.65	50.12	50.74
−0.65	−0.80	50.30	51.02
−0.80	−0.50	50.21	50.86
−0.50	−0.88	50.28	50.97
−0.88	−0.78	50.45	51.25
−0.78	−0.75	50.10	50.86
−0.75	−0.53	50.22	50.86
−0.53	−0.60	50.25	50.82
−0.60	−0.62	50.50	51.11
−0.67	−0.62	50.40	51.04
−0.62	−1.20	50.13	51.04
−1.20	−0.72	50.20	51.16
−0.72	−0.70	50.12	50.83
−0.70	−1.40	50.80	51.85
			Mean 50.93

In Table VIII. above r_v is a measure of the energy after going through the cell and r_t is a measure of the total radiation, but to make these comparable they must be corrected. First, for distance. The deflections r_v and r_t must be reduced to the values they would have had if the source had been at some fixed distance for both (unit distance, say). That is, r_v must be multiplied by d_v^2 and r_t by d_t^2. Second, with the cell in, all of the radiation at any wave-length does not have effect upon the thermo-couple for a certain amount is absorbed by the cell. Experiments made with radiation of wave-length .55 μ proved that only 60 per cent. of the energy at that wave-length is transmitted; hence, r_v must be multiplied by 100/60. Therefore

$$\mu = \frac{100 \dfrac{r_v \times d_v^2}{60}}{r_t \times d_t^2}.$$

The values of μ given in column five are calculated from this equation for each source.

The radiation from the whole lamp was in each case allowed to fall

TABLE VI.

Tungsten (.65 w/c) 6.6 amp. With Cell.

Zero.		D	r_v
Before.	After.		
7.02	7.10	14.02	6.96
7.10	7.20	14.00	6.85
7.20	7.28	14.12	6.88
7.28	7.26	14.20	6.92
7.26	7.40	14.20	6.87
7.40	7.40	14.30	6.90
7.40	7.45	14.34	6.92
7.45	7.40	14.30	6.88
7.40	7.49	14.28	6.84
7.49	7.60	14.57	7.03
7.60	7.63	14.53	6.92
7.63	7.75	14.63	6.94
7.68	7.75	14.55	6.84
7.75	7.80	14.75	6.98
7.80	7.85	14.52	6.70
7.85	7.80	14.70	6.88
7.80	7.85	14.70	6.88
7.85	7.90	14.76	6.89
7.90	7.89	14.70	6.81
7.89	7.88	14.90	7.02
7.88	8.00	14.85	6.91
8.00	7.95	14.95	6.98

upon the thermopile. No correction was made for the radiation from any portion of the mechanism, which is an essential part of the light source as ordinarily used. For example, no correction was made for the radiation from the chimney of the Welsbach mantle lamp. For an accurate determination of the efficiency of the mantle itself such a correction must be made, by getting a cooling curve of the chimney.[1] Such a correction would increase the efficiencies recorded above. The incandescent electric lamps used were matched in color on the photometer by Mr. Kingsbury of the photometrical laboratory of the U. G. I. Co. against standards of approved type prepared by the Electrical Testing Laboratories, New York City.

The values for the tungsten lamps are inversely proportional to the watts per candle ratings. This is to be expected since the losses in incandescent lamps are proportional very approximately to the watts per candle.

A similar calculation based upon watts per candle for the new tungsten and for the carbon filament lamps, taking the efficiency of the tungsten

[1] Nichols, Laboratory Manual, Vol. II., p. 335.

TABLE VII.

Mazda (.65 w/c) 6.6 amp. Without Cell.

Zero.		D	r_t
Before.	After.		
9.20	8.98	35.70	26.62
8.97	9.75	36.25	26.89
9.75	9.25	35.80	26.30
9.25	8.60	35.80	26.38
8.60	8.75	35.15	26.48
8.75	8.65	35.65	26.95
8.65	8.55	35.40	26.80
8.55	9.30	35.75	26.33
9.30	8.60	35.90	26.95
8.60	8.65	35.15	26.53
8.65	9.22	35.60	26.67
9.22	9.20	36.12	26.91
9.20	9.00	35.20	26.10
8.88	8.95	35.45	26.54
8.95	10.00	36.20	26.73
10.00	9.45	36.45	26.73
9.53	8.85	36.05	26.86
8.85	7.80	35.05	26.73
7.80	8.15	34.96	26.99
8.15	7.45	34.60	26.80
7.80	7.72	34.48	26.67

(1.25 *w/c*) as 1.65, does not give the actual values observed. For the new tungsten lamp the value is 3.25, showing that the losses must be considerably more, or that the determined value of μ is too low, due to the excessive heating of the bulb. No correction was made for the hot gaseous envelope surrounding the candle and the open burner. The latter was a lava-tip burner consuming about four cubic feet of gas per hour. It had to be brought very close to the cell to get suitable deflections. At this distance the whole of the flame could not contribute to the deflection. Correcting the value of μ given above for this, the value becomes approximately 0.3 per cent. The mantle with 0.25 per cent. ceria is commercially known as "Iveslite" mantle. The one with 0.75 per cent. ceria is the mantle commonly used.

The chimney referred to above as "perforated" chimney had air rents around its base, in distinction from the solid chimney which had none. The gas was city gas of Philadelphia known as mixed gas rated at 650 B. T. U. per cu. ft. approximately; pressure 2.5 inches of water.

The mantle marked 1)*a* in the table consumed 3.8 cu. ft. per hour; 1)*b* 4.95 cu. ft. per hr.; 2) 3.6 cu. ft. per hr.; 3)*a* 4 cu. ft. per hr.; 3)*b* 5.2 cu. ft. per hr.

TABLE VIII.

Results for Various Sources.

Source.	r_v	r_t	d_v	d_t	μ	Description.
Carbon filament.....	2.28	50.92	29.17	120.52	0.45	Point source 4 w/c 99v.
Nernst glower.....	4.65	28.46	20.39	102.90	1.08	0.8 amp. stereopticon type.
Tungsten-nitrogen.....	6.89	26.72	29.53	113.13	2.93	6.6 amp. (0.65 w/c)
Open burner.....	1.50	42.19	20.88	115.52	0.19	See below
Standard candle.....	0.25	8.67	16.45	73.85	0.24	Sperm candle
Mantles (1) *a*.....	0.89	21.34	44.8	163.3	0.5	0.25% Ceria
(1) *b*.....	1.48	23.57	44.9	163.4	0.7	0.25% Ceria
(2)	1.62	22.91	43.77	162.9	0.8	2% CeO_2
(3) *a*.....	2.90	21.43	37.60	163.4	1.2	Solid Chimney
b.....	3.81	26.91	37.6	163.4	1.26	perforated, 0.75%CeO_2
Tungsten (1).....	3.65	16.28	27.75	119.47	1.99	102.6 v. 1 w/c
(2).....	3.11	14.99	27.75	119.47	1.84	97.0 v. 1.1 w/c
(3).....	2.51	13.53	27.75	119.47	1.65	9.16 v. 1.25 w/c
Mercury arc[1].....	0.44	2.4	30.0	30.0	30.5	1.7 amp.

From 1)*a* and 1)*b* mantles it is seen that the efficiency varies with the gas consumption. This is to be expected for when an insufficient supply of gas is admitted, certain portions of the mantle will be cool; also when too much gas is admitted a small bunsen flame may exist above the mantle; both these conditions will lower the value of μ. The values for the mantles with varying per cent. of ceria are what might be expected from a study of the curves showing per cent. of ceria with candle power.[2] The mantle when used first indicated a greater efficiency than after a few hours burning, but was much more unsteady. Just how the radiant luminous efficiency changes for small changes in consumption at the point where the mantle is just filled and at its brightest would require more accurate measurements and steadier conditions. Two other determinations were made for the 4 *w/c* carbon lamp which make the mean value of μ equal to .43 per cent.

The Heraeus quartz arc at 10 amperes was also tried for efficiency. The quartz tube was between 6 and 8 cm. long and a portion of the tube only used. A screen of heavy cardboard with an aperture 2 cm. horizontally by 3 cm. vertically was placed immediately in front of the arc, in such a manner that it could be dropped and put in place only when deflections were taken. This was to insure that the screen itself would remain at room temperature. Values obtained for the arc are unsatisfactory. Taking measurements immediately after starting gave a value

[1] Pfund's Type, PHYS. REV., N. S., Vol. III., No. 4, April, 1914.

[2] Johns Hopkins Lectures on Illuminating Engineering, M. C. Whittaker.

in μ in the neighborhood of 7 per cent. This value would steadily decrease for hours afterwards due to heating up of the tube.

Measurements were made in Baltimore with the new type of mercury arc recently described by Pfund.[1] The apparatus used was the same as that described in the first part of this paper. For Pfund's thermo-element as used, there was substituted the Ruben's thermopile as used in the measurements of the previous efficiencies. The procedure in this case was identical with the previous. The thermopile was carefully shielded and screens were placed at intervals between it and the source. The portion of the lamp just above the mass of mercury at the positive electrode was studied, the rest of the lamp being carefully screened off. This portion was 1.3 cm. wide by 1.8 cm. high. The lamp was placed 32 cm. from the thermopile and it was found unnecessary to move it. Even with the cell in place readable deflections were obtained. The current was 1.8 amp. taken from a storage battery with lamps in series as resistance.

Table IX. gives the zero position before and after in column 1; the position of maximum deflection, column 2; the magnitude of the deflections, column 3; both with the cell in place and without the cell.

To determine the correction to be applied due to the radiation from the walls of the tube, the lamp was put out and the time noted. Imme-

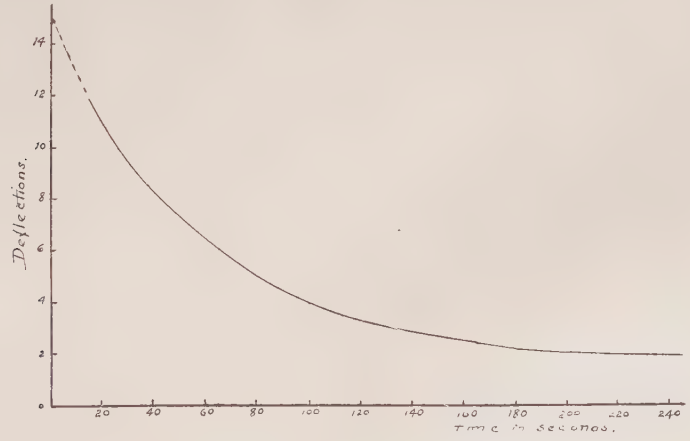

Fig. 5.

diately thereafter the screen was drawn aside allowing the radiation from the dark hot tube to fall upon the thermopile. The deflection and the time were again noted. Several other deflections were obtained and times at which they were gotten were noted, while the tube cooled. These deflections and times reckoned in seconds are plotted in Fig. 5.

By exterpolation the deflection due to the radiation from the walls just at the time the lamp was quenched was obtained. This deflection was subtracted from the deflections recorded for total radiation. From the corrected deflections the value of the efficiency was then calculated. This is rather surprisingly high. This may be partly accounted for by the fact that the energy in the extreme violet and ultra-violet is not effective under this arrangement. Without correcting for the hot walls the value is only 4.2 per cent. This type of mercury arc, however, affords a very nice means of getting the radiant luminous efficiency through the quartz plate sealed to the upper end of the tube. By using a right-angled quartz prism much of the effect due to the heated tube could be at once eliminated. No such measurement was made at this time.

The carbon arc was found too unsteady to get reliable measurements. Magnetite electrodes were received from Dr. Whitney, of the General Electric Laboratory, and various luminous carbons from Mr. Chillis, of the National Carbon Co. It is hoped that these will be studied in the near future.

TABLE IX.

Zero With Cell, Mm.	P_m, Cm.	Deflection, Cm.
0, −.3	.40	.41
0, −.3	.40	.41
0, 0	.43	.43
0, −.5	.42	.44
0, −.5	.43	.45
0, —.3	.45	.46
0, — 0	.47	.47
0, −.2	.44	.45
0, — 0	.45	.45
		Mean.....44
Without cell		
0, 1 1	17.7	17.2
0, .4	17.4	17.2
0, .5	17.4	17.2
0, .5	17.9	17.7
0, .2	17.4	17.3
0, .2	17.5	17.4
0, .4	17.9	17.7
0, .2	17.4	17.3
0, .2	17.6	17.5
		Mean.....17.4

This work was suggested by Dr. H. E. Ives while the writer was working in the research laboratory of the United Gas Improvement Company of Philadelphia during the summer of 1913. To him the

writer is greatly indebted for suggestions, for the standard illuminants used and for the many facilities placed at his disposal while measurements on efficiencies were made.

The writer wishes to express his appreciation of the interest of Professor Ames in this work and of the other members of the physics faculty, especially of Dr. Pfund, to whom grateful acknowledgment is made for suggestions and encouragement throughout the work.

Johns Hopkins University,
June, 1914.

VITA

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